

# Differentiating (3+1) from (3+n) Models

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Joint Superbeams / Neutrino Factory Workshop

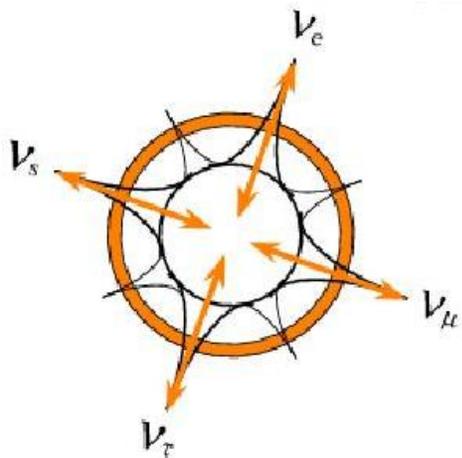
APS Neutrino Study, FNAL, May 13-14, 2004

## Outline

- Motivations for sterile neutrino models
- Five possibilities considered here:
  1. Current experimental constraints on (3+1) and (3+2) models
  2. Constraints from null MiniBooNE  $\nu_\mu \rightarrow \nu_e$  result
  3. MiniBooNE confirms LSND:  $\nu_\mu \rightarrow \nu_e$  energy spectrum
  4. MiniBooNE  $\bar{\nu}$  mode: CP-violation at short-baselines ((3+n) only)
  5.  $\nu_\mu$  disappearance .vs. baseline at  $\nu$ -SNS

# Theoretical Motivations

- Sterile neutrinos = neutrinos with no standard weak couplings
- Proposed mechanisms to generate neutrino masses often involve adding right-handed neutrinos to the Standard Model
- Light sterile neutrinos can be hard to find experimentally, but not theoretically!  
Just pick your favorite theoretical direction. . .

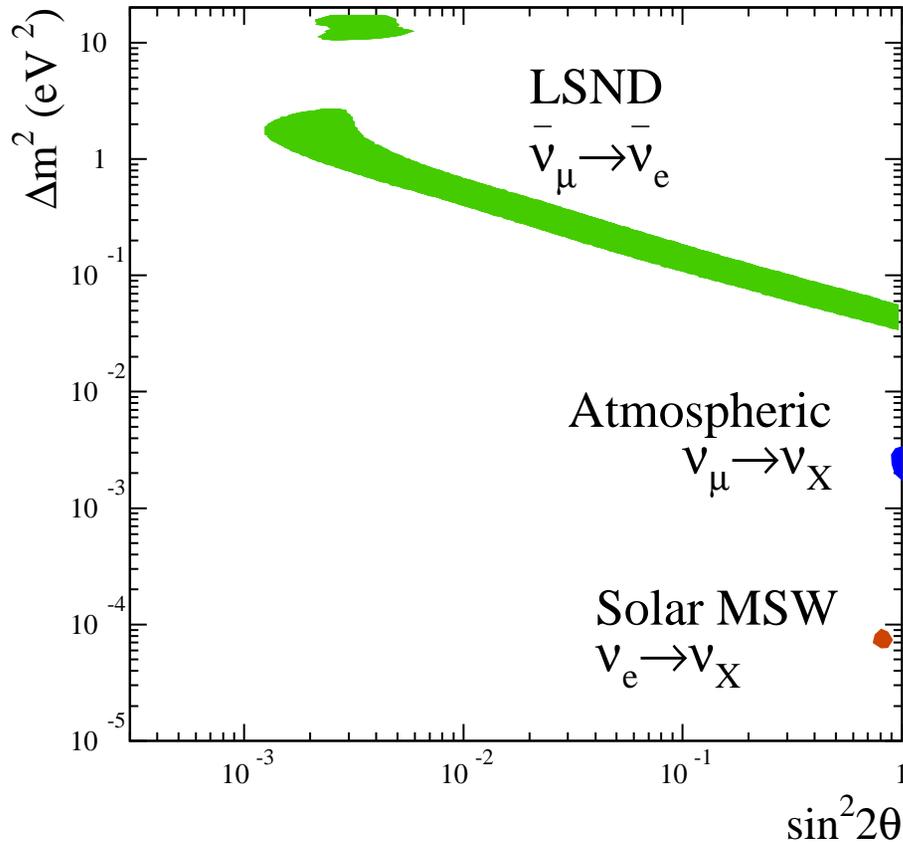


- **Grand Unified Theories**  
Mohapatra, [hep-ph/0107264](#), McKeller et al., [hep-ph/0106121](#), . . .
- **SuperSymmetry**  
Dvali et al., [hep-ph/9810257](#), Arkhani-Amed et al., [hep-ph/0006312](#), . . .
- **Extra-Dimensions**  
Ioannisian et al., [PRD63 073002](#), Ma et al., [hep-ph/0006340](#), . . .

- Important to mention sterile neutrinos in APS neutrino study

# Experimental Motivations

- There are three experimental hints pointing toward neutrino oscillations:



- Two-neutrino oscillation approximation:

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos \vartheta & \sin \vartheta \\ -\sin \vartheta & \cos \vartheta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\Delta m^2 = m_2^2 - m_1^2$$

- Oscillation probabilities:

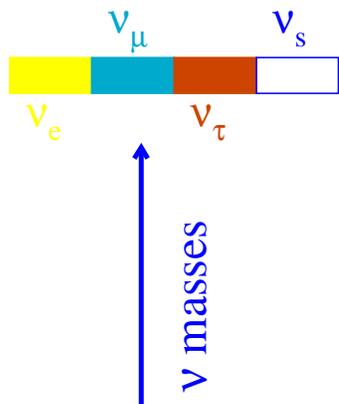
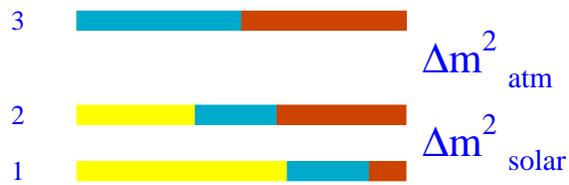
$$P_{\nu_\alpha \rightarrow \nu_\beta} = \sin^2 2\theta_{\alpha\beta} \sin^2(1.27 \Delta m^2 L/E), \quad \alpha \neq \beta$$

$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta_{\alpha\alpha} \sin^2(1.27 \Delta m^2 L/E)$$

- $\Delta m_{sol}^2 + \Delta m_{atm}^2 \neq \Delta m_{LSND}^2 \Rightarrow$  need at least three independent mass splittings?

# If LSND is NOT due to oscillations...

- From the experimental point of view, there is no need to introduce active-sterile neutrino mixing (even though it is still a possibility)



Solar  $\nu_e \rightarrow \nu_e, \nu_e \rightarrow \nu_{\mu,\tau}$

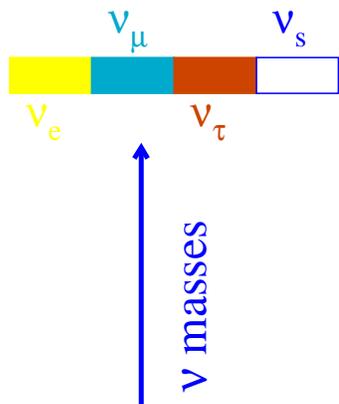
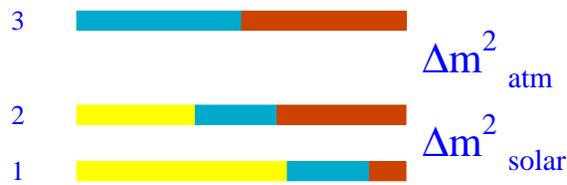
Reactor  $\bar{\nu}_e \rightarrow \bar{\nu}_e$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atm and long baseline  $\nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\tau$

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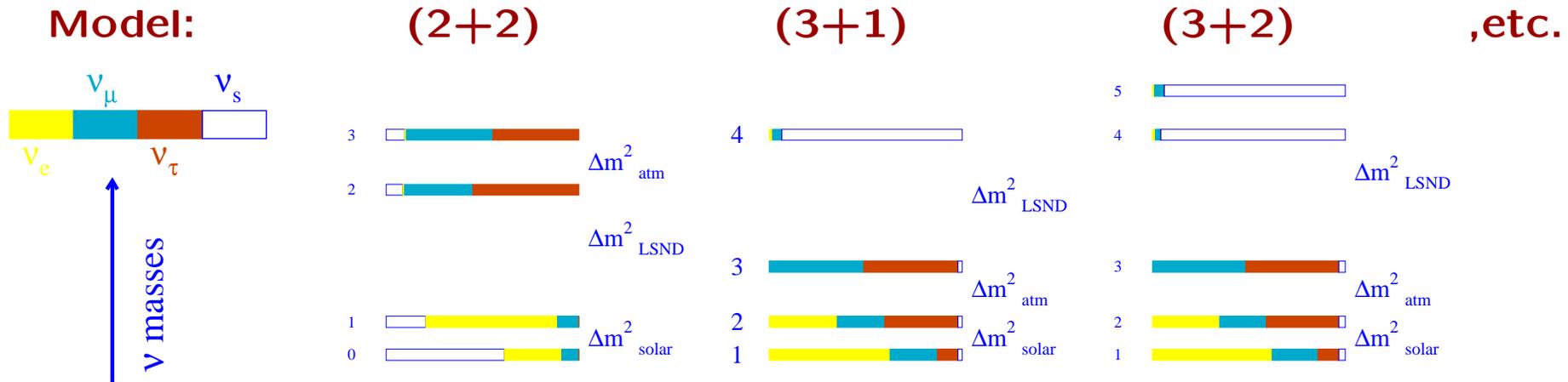
Atm and long baseline  $\nu_\mu \rightarrow \nu_\mu, \nu_\mu \rightarrow \nu_e, \nu_\mu \rightarrow \nu_\tau$

$$|U| = \begin{pmatrix} 0.70 - 0.87 & 0.50 - 0.69 & < 0.16 \\ 0.20 - 0.61 & 0.34 - 0.73 & 0.60 - 0.80 \\ 0.21 - 0.63 & 0.36 - 0.74 & 0.58 - 0.80 \end{pmatrix}$$

(Bandyopadhyay *et al.*, PLB 559, 2003)

# If LSND is due to oscillations...

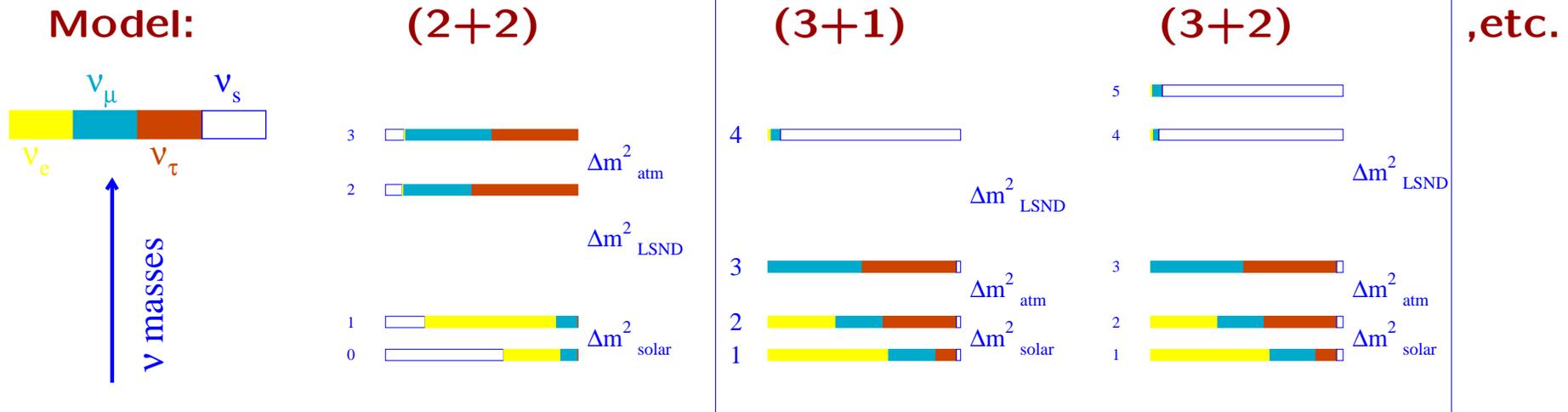
- CPT-conserving models, with sterile neutrinos:



- CPT-violating models, without/with sterile neutrinos
- Mass varying neutrinos

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- CPT-conserving models, with sterile neutrinos:



- CPT-violating models, without/with sterile neutrinos
- Mass varying neutrinos

I will discuss SBL experimental constraints on these models  
(work in collaboration with J. Conrad, M. Shaevitz, K. Whisnant)

# Combined analysis of existing SBL results

- Short-baseline experiments on

- $\nu_\mu$  disappearance (CCFR84, CDHS)
- $\bar{\nu}_e$  disappearance (Bugey, CHOOZ)
- $\nu_\mu \rightarrow \nu_e$  appearance (LSND, KARMEN, NOMAD)

probe the same  $\Delta m^2$  range and the same matrix elements:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \nu_{s'} \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & U_{e5} & \dots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & U_{\mu5} & \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & U_{\tau5} & \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & U_{s5} & \\ U_{s'1} & U_{s'2} & U_{s'3} & U_{s'4} & U_{s'5} & \\ \dots & & & & & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \vdots \end{pmatrix}$$

# Combined analysis of existing SBL results

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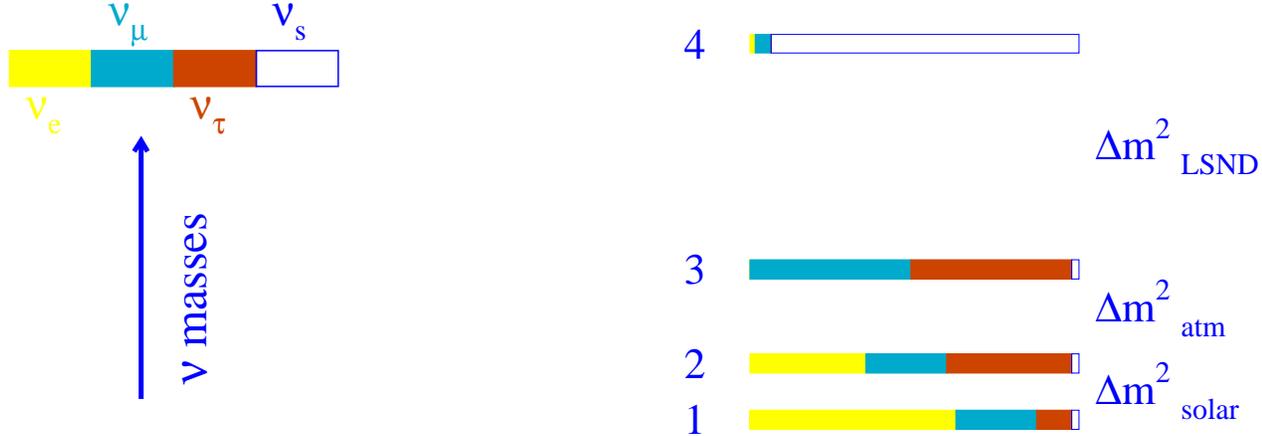
- $\nu_\mu$  disappearance (CCFR84, CDHS)
- $\bar{\nu}_e$  disappearance (Bugey, CHOOZ)
- $\nu_\mu \xrightarrow{(-)} \nu_e$  appearance (LSND, KARMEN, NOMAD)

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- Only LSND demands  $U_{e4}U_{\mu4} \neq 0$ , or  $U_{e5}U_{\mu5} \neq 0$ , etc.
- Is LSND consistent with the upper limits on active-sterile mixing at high  $\Delta m^2$  derived by the null short-baseline experiments (NSBL)?
- NSBL = Bugey + CHOOZ + CCFR84 + CDHS + KARMEN + NOMAD

# (3+1) models and SBL experiments



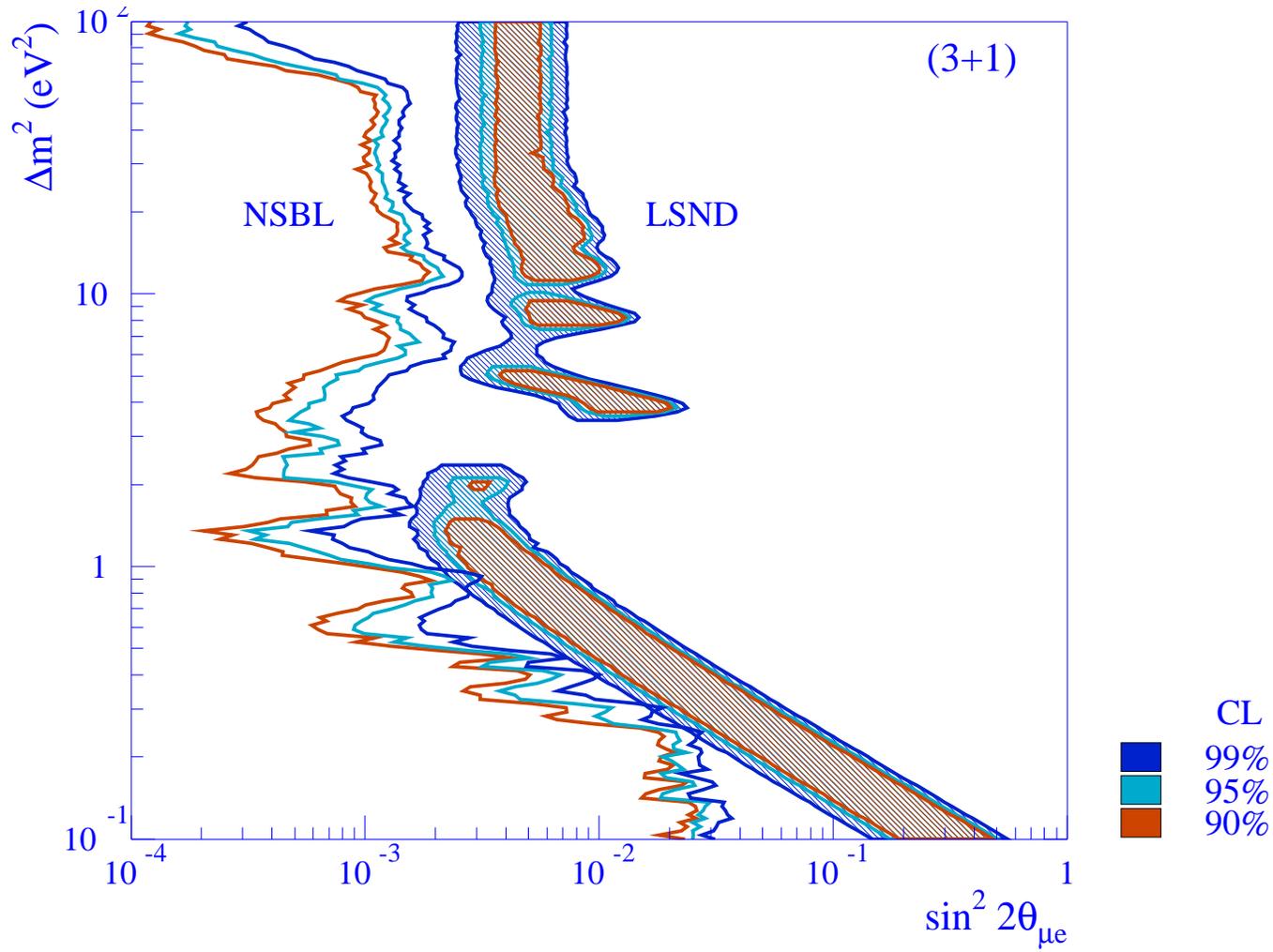
- Three parameters probed:  $\Delta m_{41}^2$ ,  $U_{e4}$ ,  $U_{\mu 4}$  (SBL only: can assume  $\Delta m_{21}^2 = \Delta m_{32}^2 = 0$ )
- Oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27 \Delta m_{41}^2 L/E)$$

- Two-neutrino approximation is satisfied  $\Rightarrow$  define:

$$\Delta m^2 \equiv \Delta m_{41}^2, \quad \sin^2 2\theta_{\mu e} \equiv 4U_{e4}^2 U_{\mu 4}^2$$

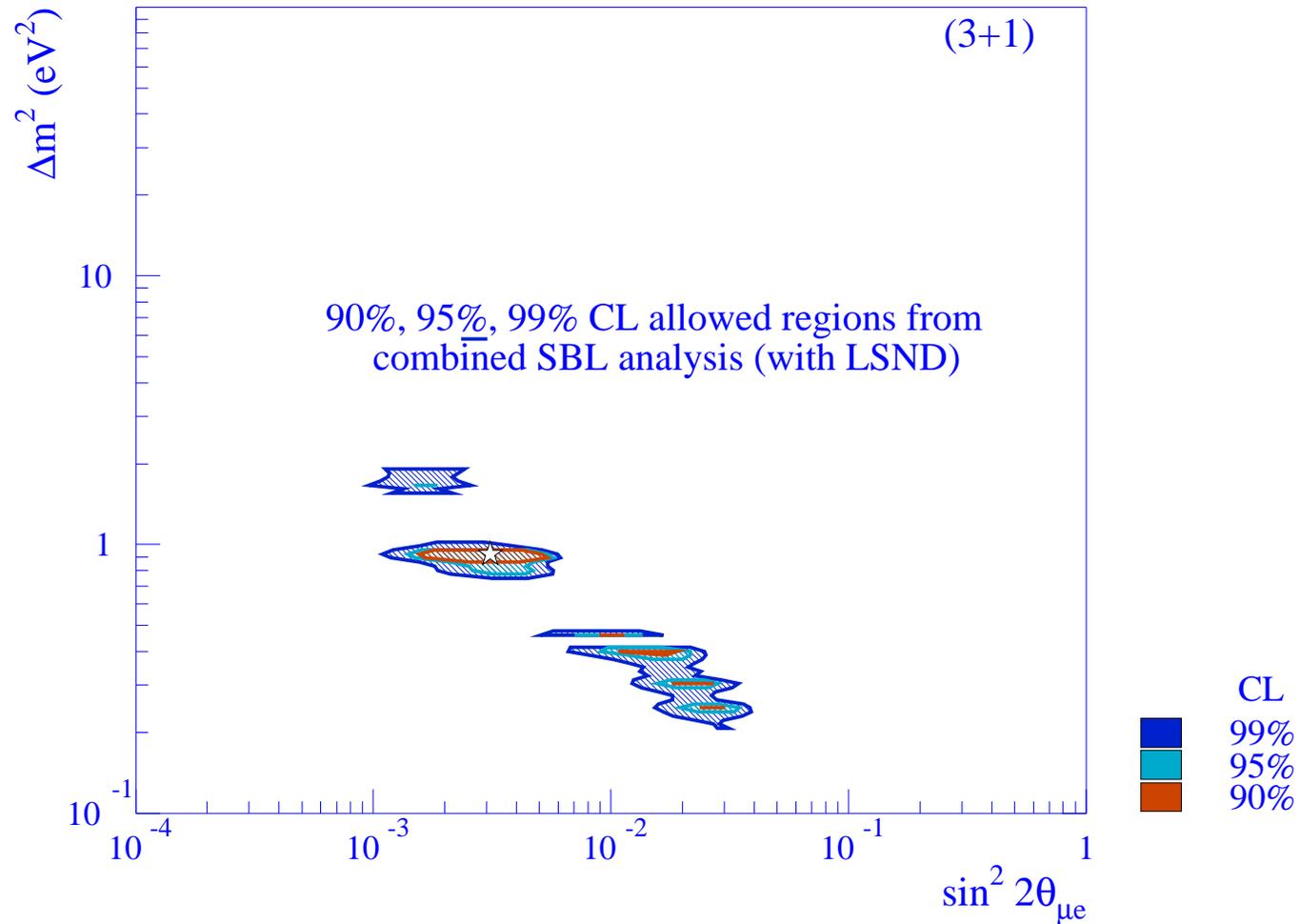
# Are (3+1) Models Allowed?



- NSBL and LSND data sets are only marginally consistent with each other

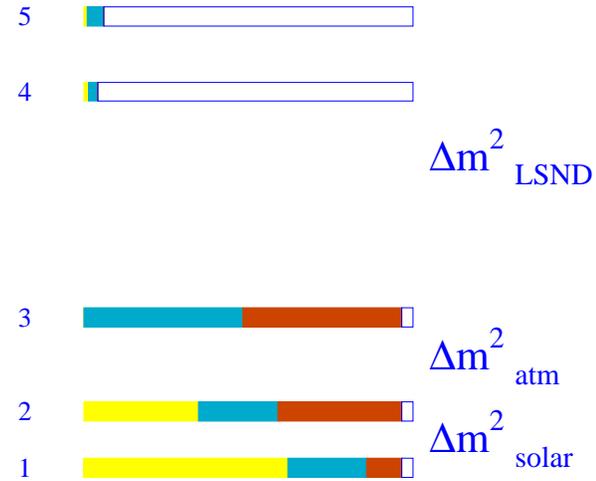
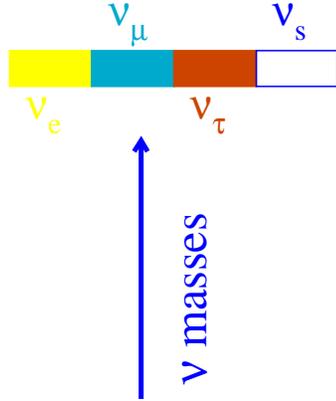
# Favorite (3+1) Models

- Assuming statistical compatibility of all SBL results, a joint analysis gives:



- Best-fit:  $\Delta m^2 = 0.92 \text{ eV}^2$ ,  $U_{e4} = 0.136$ ,  $U_{\mu 4} = 0.205$

# (3+2) models and SBL experiments



- Six parameters probed (CP-conserving case):  $\Delta m_{41}^2$ ,  $U_{e4}$ ,  $U_{\mu 4}$ ,  $\Delta m_{51}^2$ ,  $U_{e5}$ ,  $U_{\mu 5}$
- More than one  $\Delta m^2$  contributes to the oscillation probability:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4(U_{e4}U_{\mu 4} + U_{e5}U_{\mu 5})(U_{e4}U_{\mu 4} \sin^2 x_{41} + U_{e5}U_{\mu 5} \sin^2 x_{51}) - 4U_{e4}U_{\mu 4}U_{e5}U_{\mu 5} \sin^2 x_{54}$$

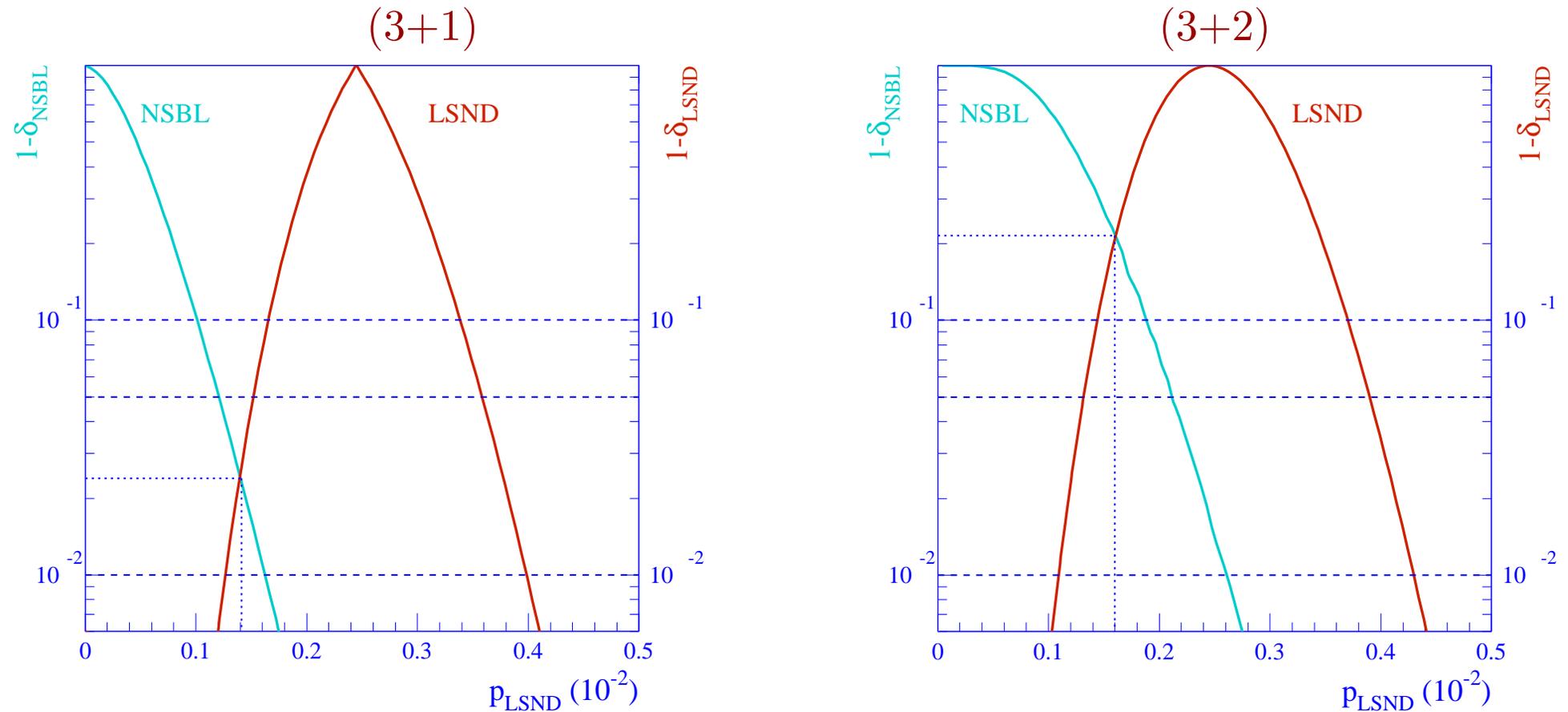
$$x_{ji} \equiv 1.27 \Delta m_{ji}^2 L/E$$

- Use NSBL data to derive the upper limits on the  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$  probability averaged over the LSND  $L/E$  distribution:

$$p_{LSND} \equiv \langle P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \rangle_{LSND}$$

# Are (3+2) Models More Compatible with Data?

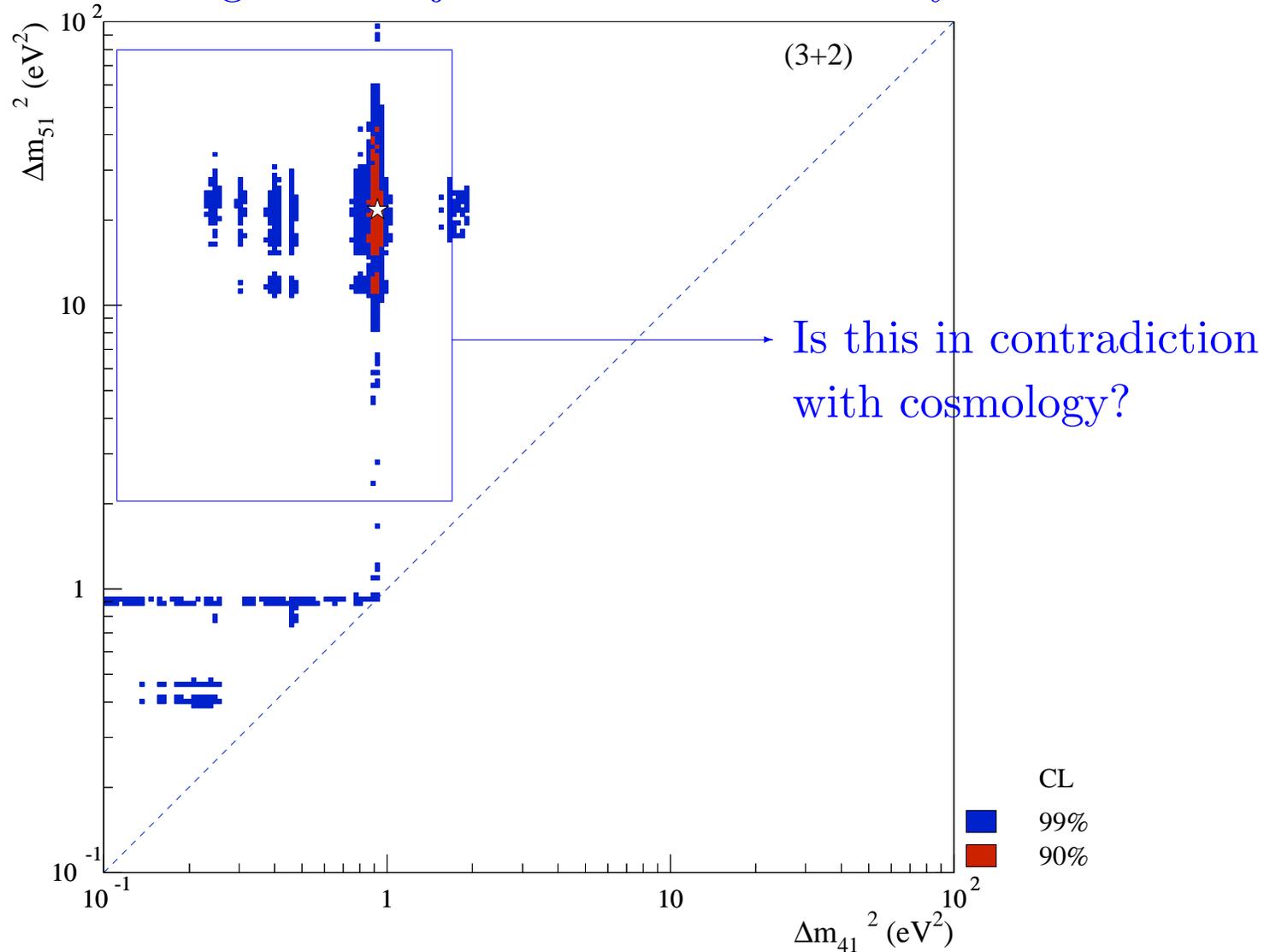
- Allowed values for the LSND oscillation probability ( $\delta =$  confidence level value):



- Two sterile neutrino models fit SBL data significantly better

# Favorite (3+2) Models

- $(\Delta m_{41}^2, \Delta m_{51}^2)$  allowed region from joint NSBL+LSND analysis:



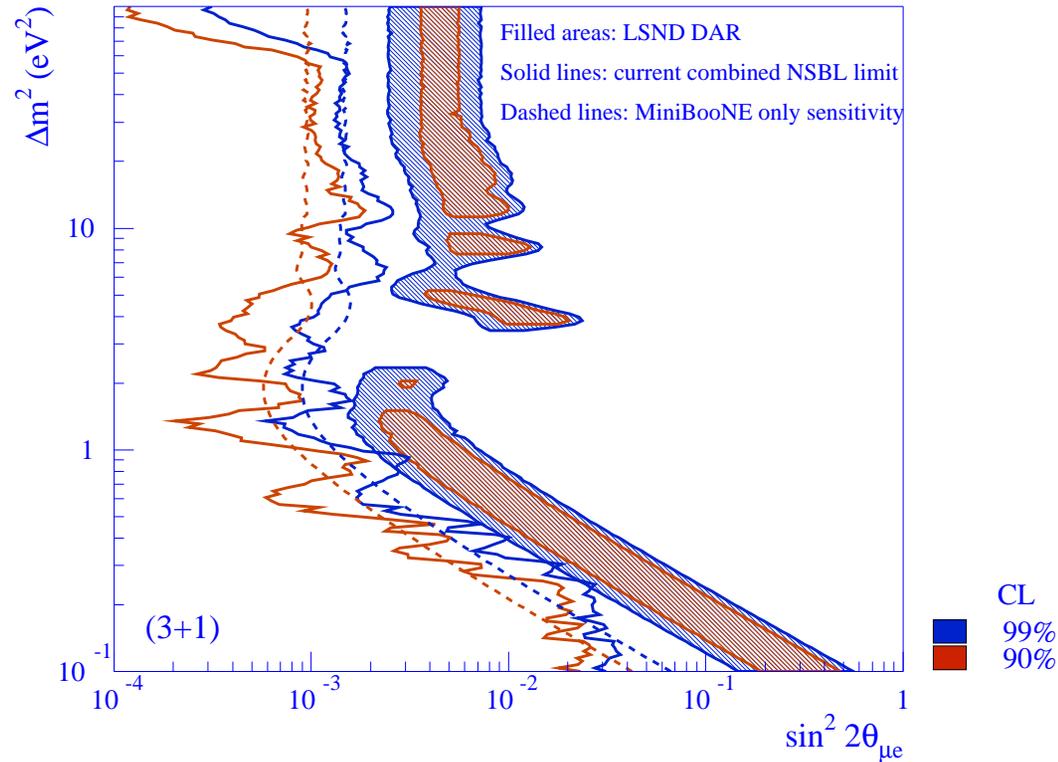
- Best-fit:

$$\Delta m_{41}^2 = 0.92 \text{ eV}^2, U_{e4} = 0.12, U_{\mu 4} = 0.20, \Delta m_{51}^2 = 22 \text{ eV}^2, U_{e5} = 0.04, U_{\mu 5} = 0.22$$

# Impact of a MiniBooNE null $\nu_\mu \rightarrow \nu_e$ Result

- Based on Run Plan sensitivity (Nov '03 PAC):

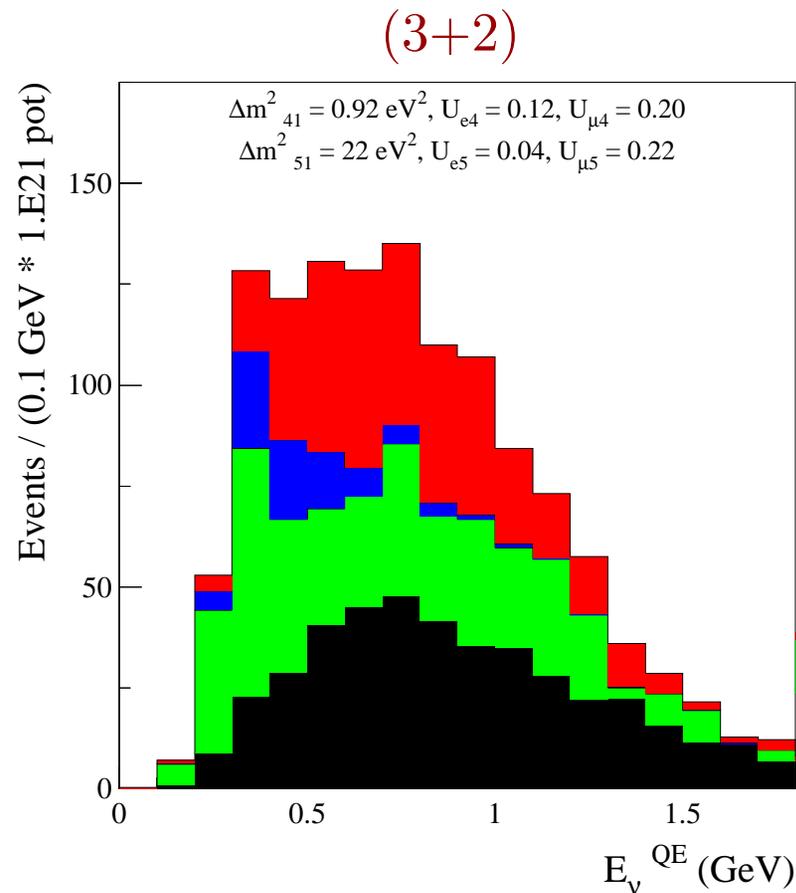
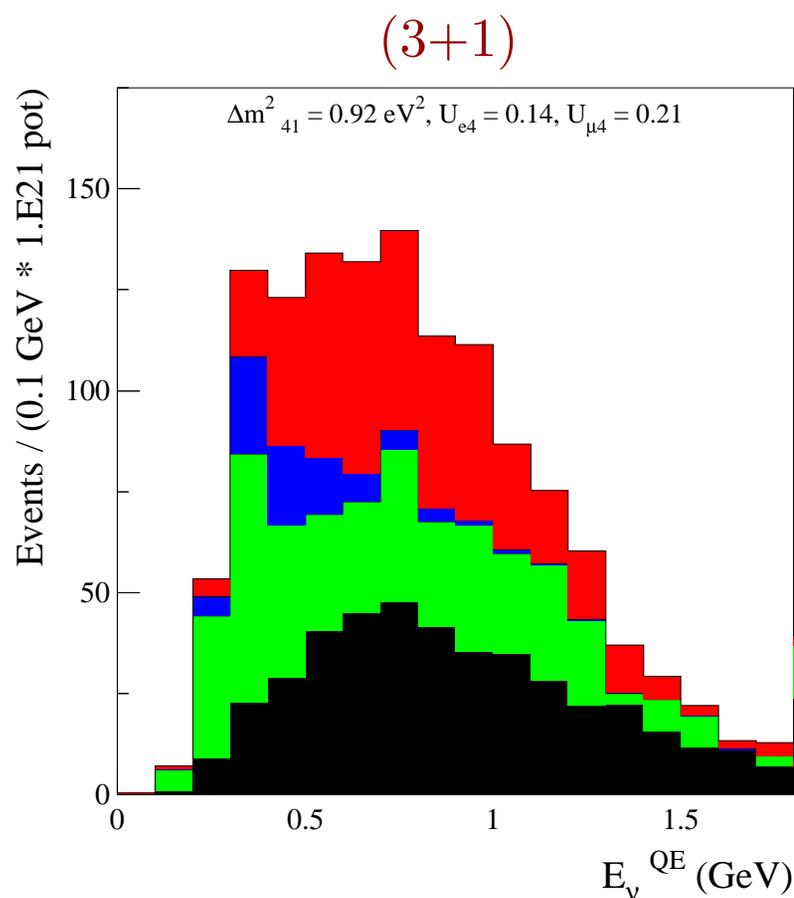
<http://www-boone.fnal.gov/publicpages/runplan.ps.gz>



- MiniBooNE-only sensitivity for  $10^{21}$  protons on target is  $\simeq 2$  times better than current, combined NSBL upper limit, in the favorite  $\Delta m^2$  ranges
- Impact on (3+n) models: work in progress. . .

# Differentiating (3+1) from (3+2) via MiniBooNE Energy Spectrum?

- Typical (3+1) and (3+2) give almost identical reconstructed neutrino energy distributions in MiniBooNE  $\Rightarrow$  very hard to distinguish
- Intrinsic  $\nu_e$  bgr,  $\pi^0$  misID bgr, radiative  $\Delta$  misID bgr,  $\nu_\mu \rightarrow \nu_e$  signal



# CP-violation at SBL

- CP-violation is possible when more than one  $\Delta m^2$  participates in the oscillation
- For (3+2) models:

$$P(\nu_{\mu}^{(-)} \rightarrow \nu_e^{(-)}) = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 x_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2 x_{51} + \\ + 8|U_{e4}||U_{\mu4}||U_{e5}||U_{\mu5}| \sin x_{41} \sin x_{51} \cos(x_{54} \pm \phi_{54})$$

$$x_{ji} \equiv 1.27 \Delta m_{ji}^2 L/E, \quad \phi_{54} \equiv \arg(U_{e4}^* U_{\mu4} U_{e5} U_{\mu5}^*)$$

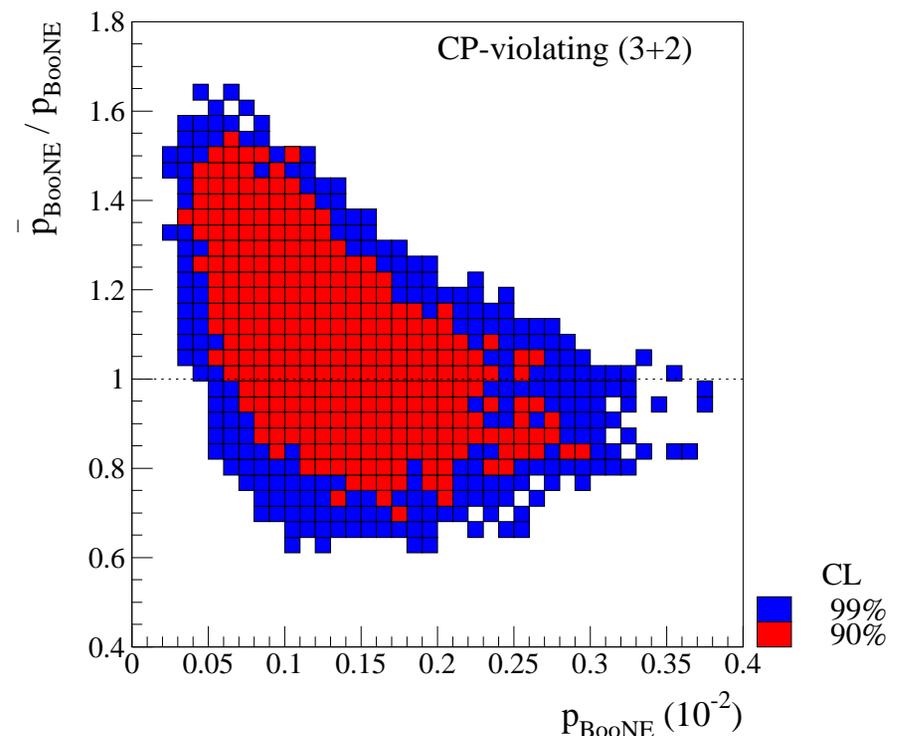
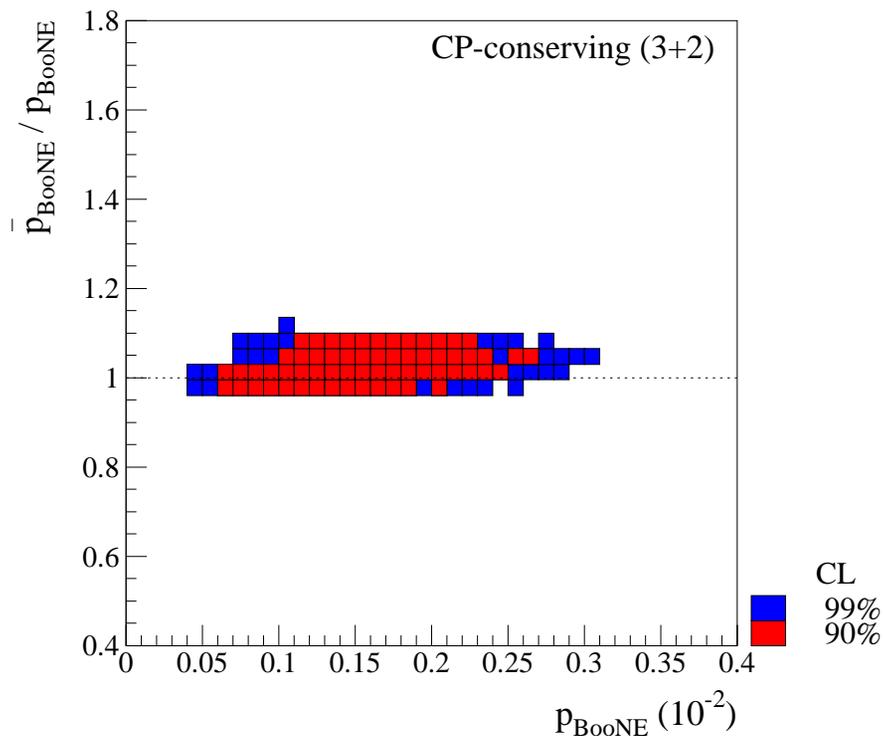
- The SBL CP-violating phase,  $\phi_{54}$ , is different from the “standard” CP phase  $\delta$ :
  - $\phi_{54}$  is associated with  $\Delta m_{41}^2$ ,  $\Delta m_{51}^2$
  - $\delta$  is associated with  $\Delta m_{21}^2$ ,  $\Delta m_{31}^2$

# MiniBooNE $\nu$ .vs. $\bar{\nu}$ running mode expectations for (3+2) models

- Compare oscillation probabilities in  $\nu$  and  $\bar{\nu}$  running mode:

$$p_{\text{BooNE}} \equiv \langle P(\nu_{\mu}^{(-)} \rightarrow \nu_e^{(-)}) \rangle_{\nu \text{ mode}}, \quad \bar{p}_{\text{BooNE}} \equiv \langle P(\nu_{\mu}^{(-)} \rightarrow \nu_e^{(-)}) \rangle_{\bar{\nu} \text{ mode}}$$

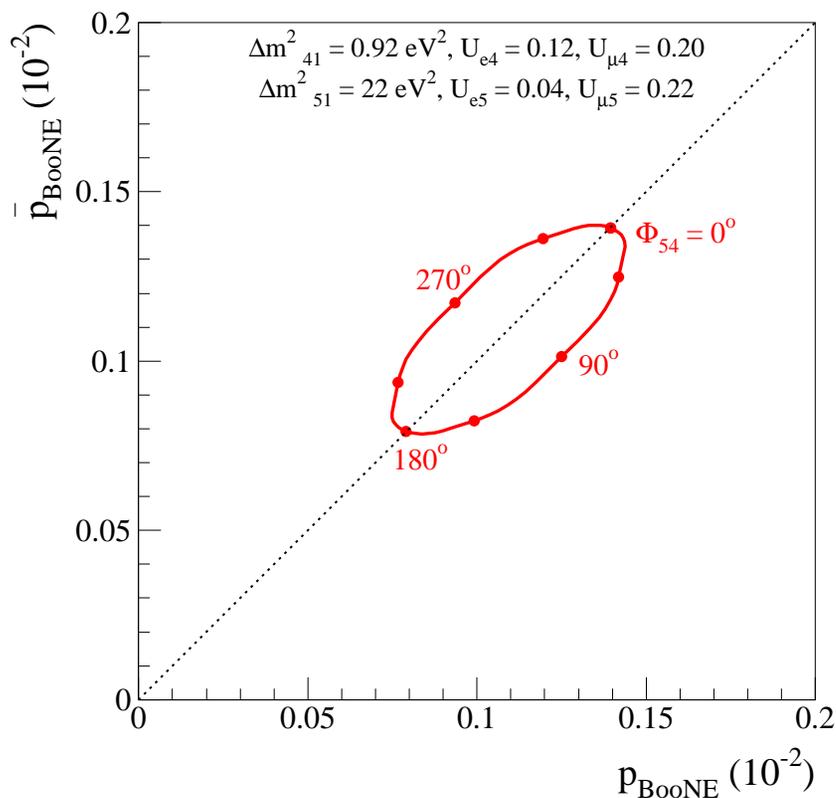
- Asymmetry, based on (3+2) models allowed by present SBL constraints (considering “wrong sign” neutrinos contribution as well):



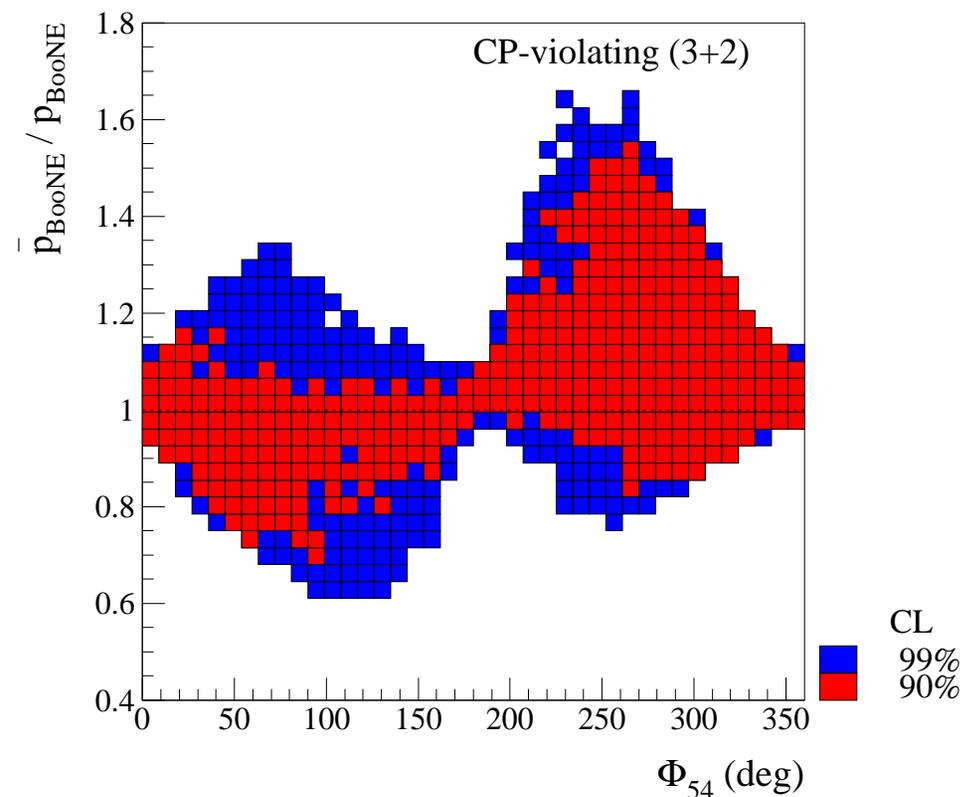
# Dependence of MiniBooNE $\nu/\bar{\nu}$ running mode oscillations on CP-violating phase

- Present SBL constraints allow for all possible CP-phase values
- Large ( $\simeq 50\%$ ) differences in MiniBooNE  $\nu/\bar{\nu}$  running mode results are possible, and might be measurable  $\Rightarrow$  establish (3+n) models and measure  $\phi_{54}$ ?

Fix masses and mixings

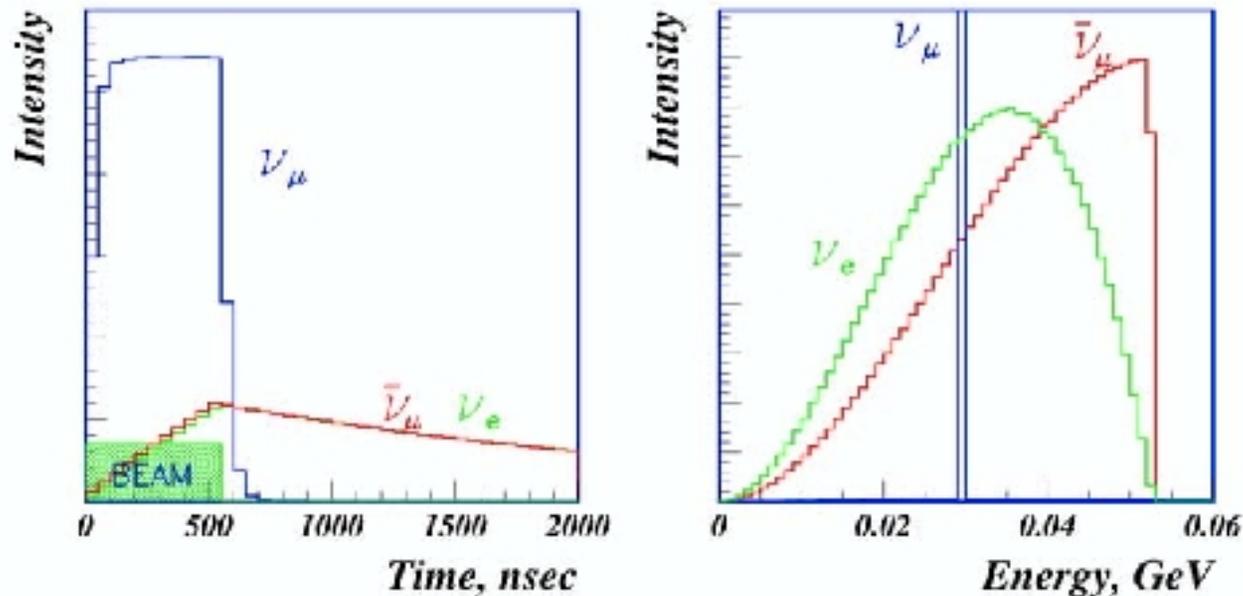


Scan over allowed masses and mixings



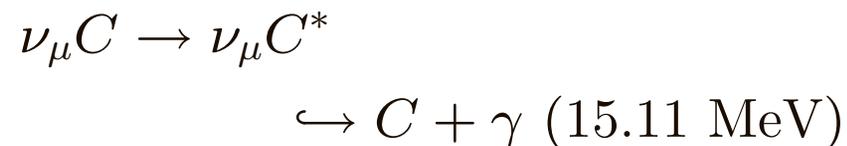
# Neutrinos at SNS: $\nu$ -SNS

- 1.3 GeV, 1.1 mA proton source, giving:
  - $\simeq 10^{15} \nu_{\mu}/s$  from  $\pi^+$  DAR ( $\simeq 4 \cdot 10^{-5}$  duty factor)
  - $\simeq 10^{15} \bar{\nu}_{\mu}/s$  from  $\mu^+$  DAR ( $\simeq 4 \cdot 10^{-4}$  duty factor)
  - $\simeq 10^{15} \nu_e/s$  from  $\mu^+$  DAR ( $\simeq 4 \cdot 10^{-4}$  duty factor)
- $\nu$ -SNS near detector: 21 m from  $\nu$  source, 20 ton detector  
Proposal is being worked on. (Contact Yuri Efremenko for details on the experiment, Richard Van de Water for  $\nu$ -SNS oscillation physics)
- Possible to build far detector: 100 m baseline, 800 tons



# Search for $\nu_\mu$ disappearance at high $\Delta m^2$ in $\nu$ -SNS

- (3+n) models, but not (3+1) models, often involve large  $\nu_\mu$  disappearance from  $\Delta m^2 \simeq 10 - 30 \text{ eV}^2$  oscillations
- Possible to look for oscillatory behavior over detector volume of 30 MeV  $\nu_\mu$ 's (monochromatic neutrinos!)
- Beam timing and 15.11 MeV  $\gamma$  tag NC  $\nu_\mu$  interaction:



- Number of expected  $\nu_\mu$  events per year in a 10 ton detector:

$$N \sim \Phi_\nu \cdot \sigma_\nu \cdot (\#CH_2) \sim (3.2 \cdot 10^{-42} \text{ cm}^2) \cdot (8 \cdot 10^{14} \text{ cm}^{-2}) \cdot (4.3 \cdot 10^{29}) \sim 1000$$

- $\sim 50$  cm neutrino pathlength resolution, from spread in  $\nu$  production and  $\gamma$  interaction length
- Far detector (100 m) would be ideal to look for  $\Delta m^2 \sim 1 \text{ eV}^2$  oscillations

# Summary on (3+1) vs (3+n) models

- Current SBL constraints prefer (3+n) to (3+1) models
- MiniBooNE null  $\nu_\mu \rightarrow \nu_e$  result would eliminate (3+1) models, and possibly also (3+n) models
- If MiniBooNE sees a signal, it is hard to disentangle (3+1) from (3+n) based on signal energy shape
- CP-violation at short baselines might be measurable if (3+n) models are correct
- Large ( $\simeq 50\%$ ) differences in the  $\nu_\mu \rightarrow \nu_e$  oscillation probability in MiniBooNE  $\nu/\bar{\nu}$  running modes are possible in CP-violating (3+n) models
- Search for disappearance of monoenergetic  $\nu_\mu$ 's as a function of baseline in the  $\nu$ -SNS detectors should be sensitive to (3+n) models